An Integrated Program To Search For Habitable Planets And To Understand The Development Of Habitable Environments

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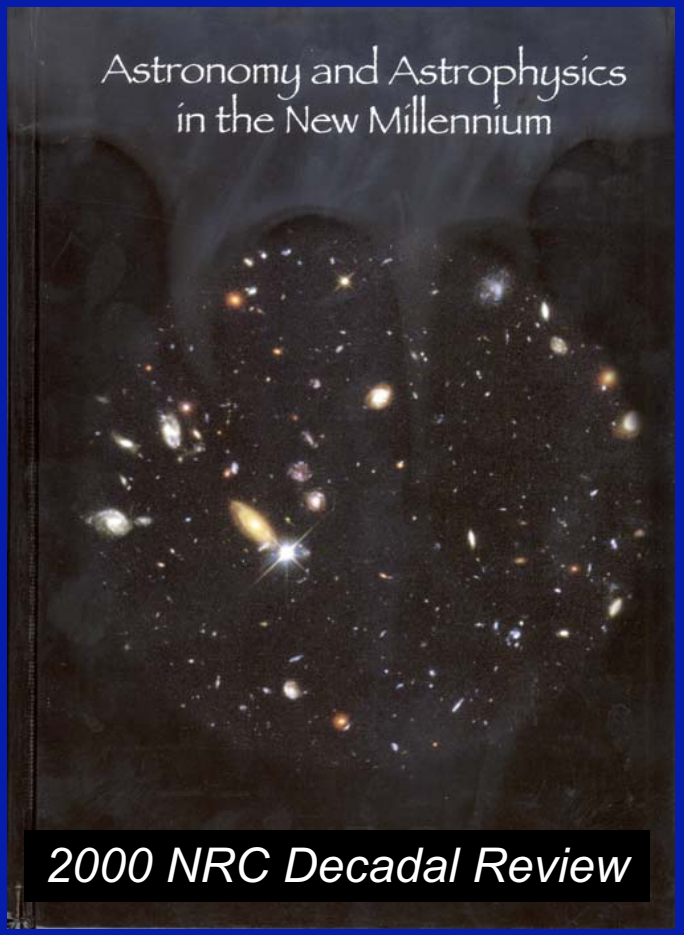
NASA Strategic Vision Goal (#4)

- How Did the Universe Become Habitable?
  - We now know that the elements of life are widespread and have their origin in the Big Bang and supernovae, but ***when, after the Big Bang, did the first habitable environments and life itself come into being?***
- Where do Planets Come From?
  - We now know that stars and planets formed together from clouds of gas and dust, but ***what processes led to planets like our own, warmed for billions of years by our sun to just the right temperature and blessed with abundant water and the elements of life?***
- Are There Other Habitable Worlds?
  - We now know that life occupies an astounding range of ecological niches on Earth, but ***are habitable environments common in other solar systems and can we use remote sensing to find other habitable or inhabited planets?***

"Conduct advanced telescope searches for Earth-like planets and habitable environments around neighboring stars."

Scientific Basis for The Search for Habitable Planets

- Planet-finding is an important question for modern astronomy
  - *"Search for life beyond Earth, and if it is found, determine its nature and its distribution [in the Galaxy]"*
- Decadal Committee recommended investment in TPF technology in the first decade of the New Millennium (2001-2010) with the expectation of starting the mission in the next decade (2010-2020)
  - *"The committee's recommendation of this mission is predicated on the assumption that TPF will revolutionize major areas of both planetary and non planetary science and that, prior to the start of TPF, ground- and space-based searches will confirm the expectation that terrestrial planets are common around solar type stars"*

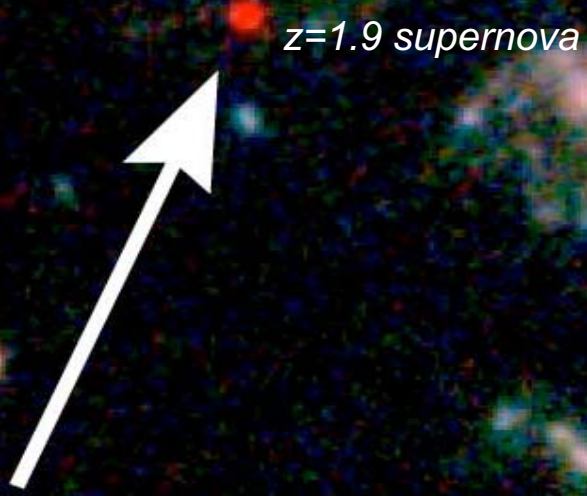


2000 NRC Decadal Review

I. How Did The Universe Become Habitable?

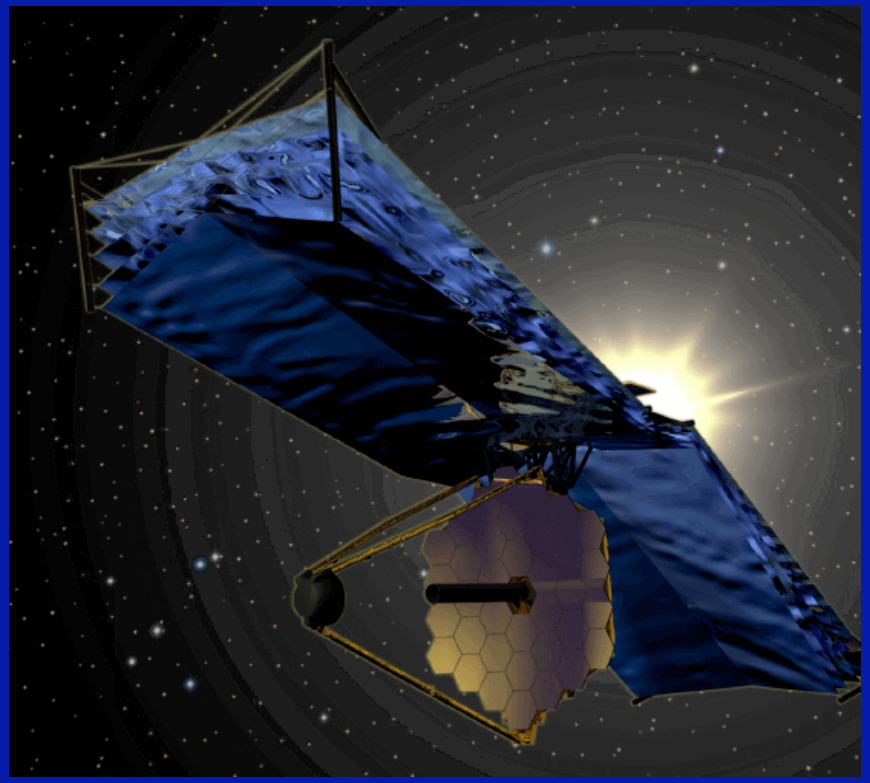
- Elements beyond H and He, forged in stars and in supernova, enrich the gas out of which subsequent generations of stars formed, eventually leading to stars capable of bearing planets and life

• Heavy elements, complex molecules, and dust are seen very soon after the Big Bang
  – Spitzer has detected Polycyclic Aromatic Hydrocarbons (PAHs) at redshift z=1.9 by (25% of current age of Universe)
  – JWST may detect PAHs at redshift z=6 (5% of current age)



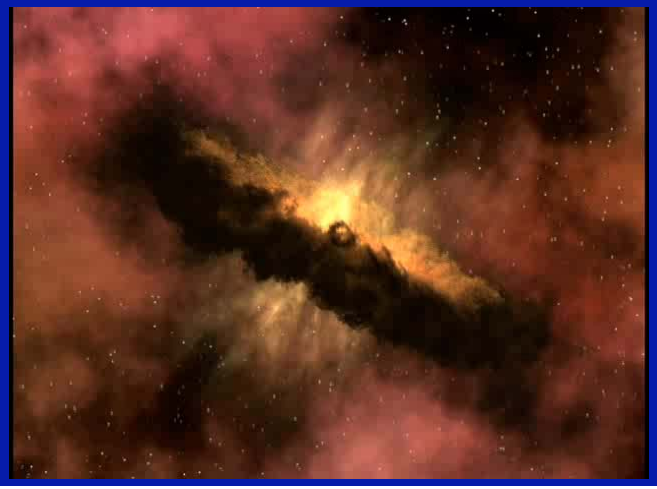
JWST Is Our Primary Mission To Address First Light, First Elements

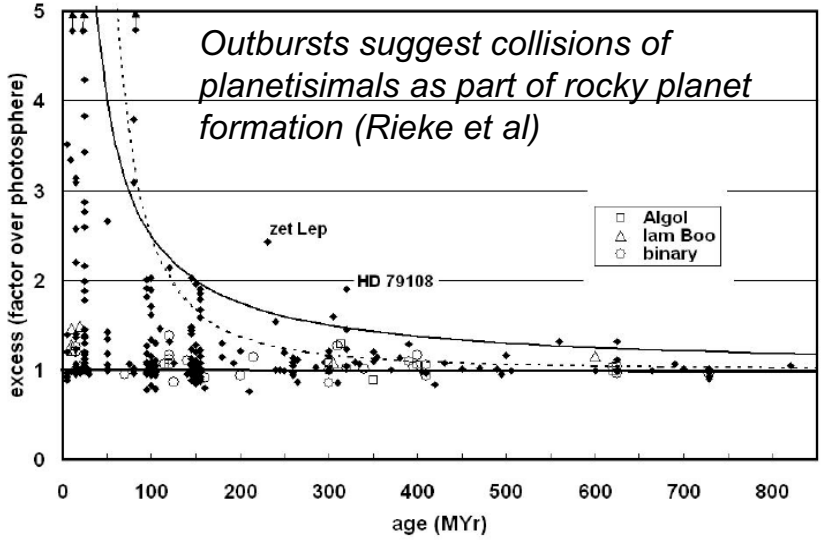
- ***NIRCAM*** will locate the first galaxies when the Universe was only a few percent of its present age.
- ***NIRSPEC*** will determine distances, physical conditions, and composition of these first stellar factories
- ***MIRI*** will confirm evolutionary status of first galaxies, uncover stars still hidden by dust, and find when the first dust grains and complex molecules first formed



II. Where Do Planets Come From?

- Planet formation is the natural accompaniment to star formation and must be understood in that context
- Modern theory and observation developed with IRAS and ground based data, through observations of disks by HST, and now by Spitzer.
- But many questions remain as we try to understand the formation of planets





Three Key Investigations for Planet Formation

- What is timescale for formation of gas giant and rocky planets?
- What controls the orbital distribution of giant planets and how might their migration affect the formation and stability of terrestrial planets?
- How are the molecules of life brought onto barren rocky planets after these were formed?

2MASS Image of star-forming Region in ρ Oph

Space Interferometer Mission (SIM) Will Make Definitive Planet Census

What We Don't Know

- Are planetary systems like our own common?
- What is the distribution of planetary masses?
  - Only astrometry measures planet masses unambiguously
- Are there low-mass planets in 'habitable zone' ?

A Deep Search for Earths

- Are there Earth-like (rocky) planets orbiting the nearest stars?
- Focus on ~250 stars like the Sun (F, G, K) within 10 pc
- Sensitivity limit of ~3 M_e at 10 pc
- ***Geoff Marcy is PI of this program***

A Broad Survey for Planets

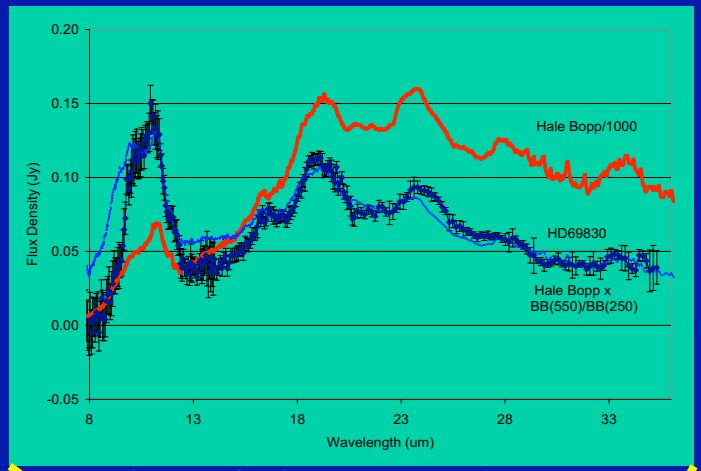
- Is our solar system unusual?
- What is the range of planetary system architectures?
- Sample 2,000 stars within ~25 pc with <<Jupiter accuracy

Evolution of Planets

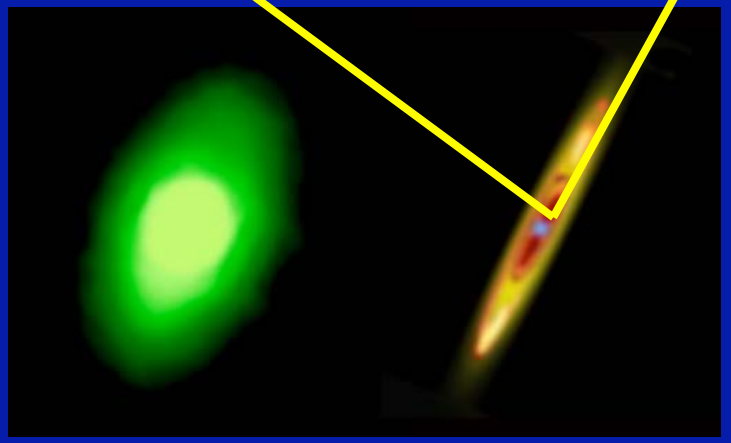
- How do systems evolve?
- Is the evolution conducive to the formation of Earth-like planets in stable orbits?
- Do multiple Jupiters form and only a few (or none) survive?
- ***CAB is PI of this program***

Additional Missions for Planet Formation

- Spitzer provides critical link between disks and planets
  - Outbursts related to planetesimal collisions
  - Cometary (Hale Bopp) material in inner solar system of nearby star
- SOFIA and Herschel probes gas with high velocity resolution to study the rotation of disk gas, study gaps and mineralogy in debris disks
- Kepler gives frequency of Earth-mass planets around solar type stars
- JWST detects hot, very young Jupiters and make resolved spatial/spectral maps of composition gradients showing ices/ mineralogy
- TPF-I images the cores of forming planetary systems directly, allowing observations at revolutionary spatial resolution



Spitzer/IRS spectrum of hot zodiacal cloud

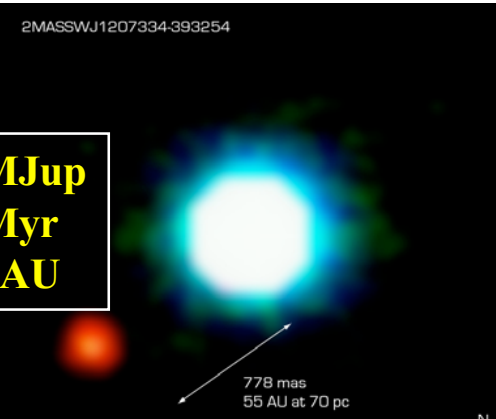


Spitzer image of Fomalhaut and JWST/MIRI prediction

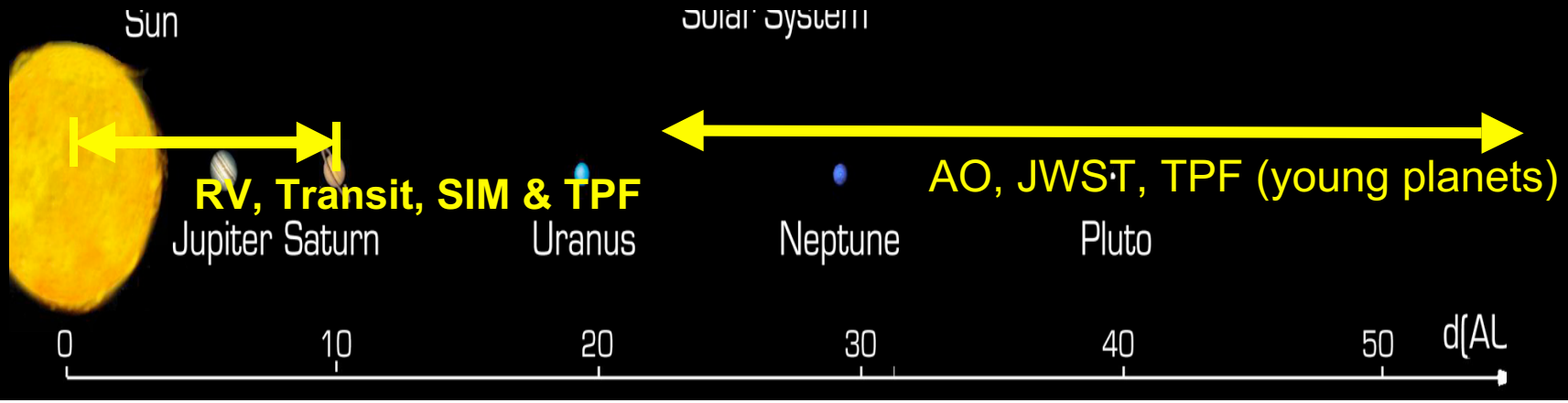
III. Are There Other Habitable Worlds?

"There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and plants and other things we see in this world."--- Epicurus (c. 300 B.C)

Detecting Planets: Big and Small, Near and Far



- Distant planets around YOUNG stars
  - ESO/VLT and other AO systems beginning to detect gas giants at 10s AU
    - NICMOS confirmation of common proper motion (Schenider et al)
  - At 5 μm NIRCAM on JWST will be powerful tool for finding distant young planets (3λ/D=0.6"@4.6 μm =30~100 AU at 50-150 pc)
- Large and small planets in inner solar system
  - Indirect detection by RV, astrometry (SIM) around nearby stars
  - Transit (ground, COROT/Kepler) and micro-lensing detection for distant stars
  - Direct detection by Keck-I/LBT-I, TPF-C/I



Tightly Integrated Program: Kepler→ SIM→TPF-C→TPF-I

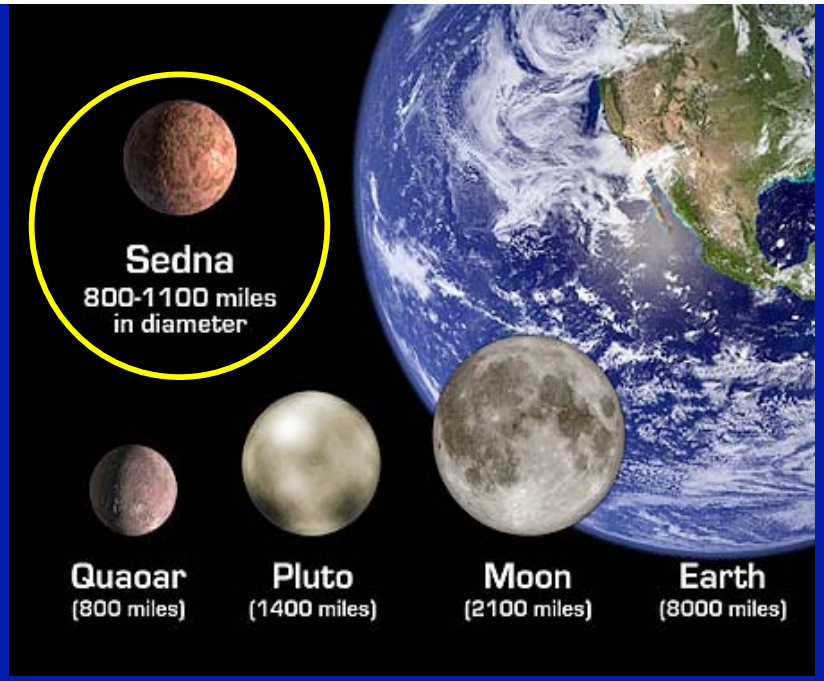
- Kepler will detect 1 Earth radius objects in Habitable Zones (HZ) around distant stars to determine $\eta_{\oplus}$
- SIM will detect first 1-10 Earth-mass objects in HZs around nearby stars
  - Determine planetary orbits and masses, critical parameters for determining habitability
  - Optimize target selection for TPF
- TPF-Coronagraph will make first direct detections of light from terrestrial planets and begin remote sensing characterization and search for signposts of life
- TPF-Interferometer will extend survey to more distant stars, complete physical characterization of planets, including habitability, and ensure robust detection capability for life

Combined Visible TPF-C and mid-IR TPF-I Yields Best Science & Robust Life Detection

- **Complete** characterization of physical properties of planets
- **Unique** determination of albedo, radius, temperature
- **Definitive** assessment of habitability
- **Unambiguous** confirmation of signatures of life

What Will We Learn About Other Earths?

- Orbital Parameters (SIM)
  - Stable orbit in habitable zone
- Characteristics for habitability
  - Temperature (TPF)
  - Temperature Variability (SIM)
  - Radius (TPF)
  - Albedo (TPF)
  - Mass (SIM)
  - Surface gravity (SIM+TPF)
  - Composition (TPF)
  - Atmospheric conditions (TPF)
  - Presence of water (TPF)
  - Temporal variability (TPF)
- Solar System Characteristics
  - Influence of other planets (SIM)
  - Presence of comets or asteroids (TPF)



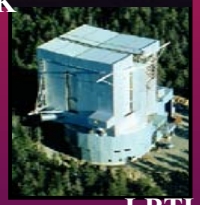
- Indicators of Life (TPF)
  - Multiple spectral lines in different wavebands confirm initial detections and extend physical interpretation
  - For planets with atmospheres (and modest cloud cover), IR characterizes atmosphere while visible sees planetary surface

Advanced Telescope for Exo-Planet Searches And Study Of Habitable Environments

Current Plans Complete

Hyperspectral Imaging

KECK



LBTI

Interferometry

SIM - PLANETQUEST

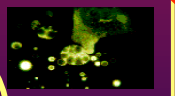
TPF - I

??

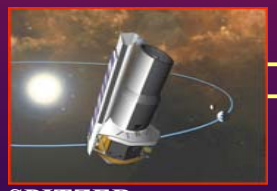
PLANET IMAGER

Kepler/Corot/RV

Hi- Res Spectroscopy



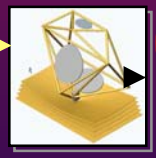
LIFE FINDER



SPITZER

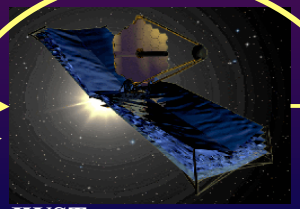
IR Cold Aperture

Large Visible Aperture



SAFIR

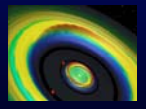
HST

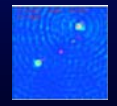


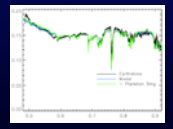
JWST

TPF - C

LARGE UV/OPTICAL OBSERVATORY







Planned Advanced Observatories

2010

2020

Visions Beyond

The Search for Habitable Planets

Missions Cover the Search for Habitable Planets and the Evolution of Habitable Environments from the Big Bang to the Present Day, From the Distant Universe to the Solar Neighborhood

	JWST	*Kepler*	*SIM*	*TPF-C*	*TPF-I*
First Stars	✵ ✵ ✵			✵	✵
First Dust & Molecules	✵ ✵ ✵				✵
Conditions for First Life	✵ ✵			✵	✵
Planet Formation timescale	✵ ✵	✵ ✵	✵ ✵ ✵		✵ ✵
Planet stability		✵ ✵	✵ ✵ ✵	✵ ✵	✵ ✵
Molecules of Life	✵ ✵ ✵			✵	✵ ✵
Other Earths in HZ		✵ ✵ ✵	✵ ✵ ✵	✵ ✵ ✵	✵ ✵ ✵
Comparative Planetology	✵	✵ ✵	✵ ✵	✵ ✵	✵ ✵ ✵
Detection of Life		✵	✵	✵ ✵ ✵ ✵	

What Will We Know In 20 Years: After Kepler, SIM, JWST, TPF-C, TPF-I?

- Where are the habitable or inhabited planets in the solar neighborhood
- In which solar systems and under what conditions, if any, do habitable or inhabited planets reside
- What are the inter-relationships between all constituents of planetary systems
  - Properties of Terrestrial Planets
  - Properties of Gas Giants 1~100 AU
  - Properties of zodiacal clouds (comets, asteroids)
- In the following 25 years, we can push to higher spectral resolution with a Life Finder Mission